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Enhanced light-extraction from a GaN waveguide using micro-pillar TiO_2–SiO_2 graded-refractive-index layers

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A GaN waveguide structure with micro-pillar arrays is designed and fabricated to measure the extraction of optical modes that would be waveguided in the absence of the pillars. Electroluminescence (EL) measurements of waveguide light-emitting diodes (LEDs) with pillar diameters in the 2–10 μm range revealed increasing light-extraction efficiency (LEE) enhancement with decreasing pillar diameter. Ray tracing simulations of LED far-field patterns confirmed experimental trends. A 54% enhancement is demonstrated for GaN waveguides cladded with a triangular lattice of graded-refractive-index (GRIN) TiO_2–SiO_2 micro-pillars of 2 μm diameters compared to GaN waveguides cladded with an unpatterned GRIN TiO_2–SiO_2 layer.

1 Introduction In GaInN LEDs, the high-refractive-index contrast at the semiconductor–air boundary produces total internal reflection and guided modes within the LED chips thereby significantly limiting their light-extraction efficiency (LEE). Photonic crystals [1–4], crystallographically formed surface textures [5, 6], and dry-etched surface textures [7] enhance light out-coupling by extracting optical modes that would otherwise be guided. Recently, graded-refractive-index (GRIN) coatings [8–10] and micro-patterned GRIN coatings [11] on GaInN LEDs have been demonstrated as effective means for enhancing the LEE. GRIN anti-reflection (AR) coatings can strongly reduce Fresnel reflections in substrates [12], LEDs [8], and photovoltaic cells [13]. Unpatterned GRIN AR coatings enhance the LEE by reducing Fresnel reflections; however, trapped guided modes remain unaffected by unpatterned AR coatings. By micro-patterning GRIN coatings, modes that would otherwise undergo total internal reflection can be extracted through the sidewalls of the micro-patterned coating. In this work, micro-patterning of a five-layer GRIN TiO_2–SiO_2 coating on a GaN waveguide is demonstrated. We show that such micro-patterned coatings enhance the extraction of optical modes from the GaN waveguide.

To analyze the extraction of light, a GaN waveguide LED test structure, shown in Fig. 1, is designed and fabricated. The purpose of the test structure is to analyze and measure the intensity of extracted modes that would otherwise undergo total internal reflection. The device has an injection, waveguiding, and light-extraction region. In the injection region, electrical injection of carriers results in photon emission from the multi-quantum well (MQW) active region underneath an opaque p-type metal contact. Guided modes from the injection region propagate within the GaN slab, *i.e.*, the waveguiding region. The light in the waveguiding region remains confined between the planar GaN–air and GaN–sapphire interface. In the light-extraction region, the light is extracted by the micro-patterned surface. The surface of the light-extraction region consists of GRIN TiO_2–SiO_2 micro-pillars, which allows light to escape through the sidewalls of the pillars.

2 Experimental methods To demonstrate the effect of micro-pillars for extracting optical modes, the GaN waveguide LED test structure shown in Fig. 1, is fabricated. GaInN LEDs emitting at 490 nm are grown on a *c*-plane sapphire substrate by metal-organic vapor-phase epitaxy and

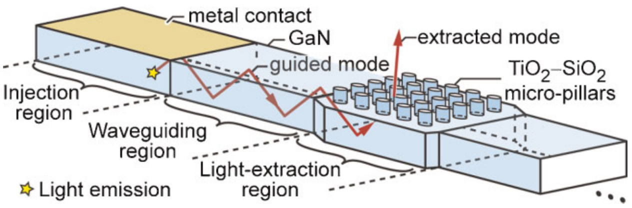

Figure 1 (online color at: www.pss-a.com) GaN waveguide LED with guided modes generated in the injection region propagating through the waveguiding region. The guided modes are extracted out of the waveguide in the light-extraction region by the GRIN TiO_2–SiO_2 micro-pillars.

consist of an n-type GaN layer, a GaInN/GaN MQW active region, and a p-type GaN layer. Standard LED fabrication processes were used to create the test structure shown in Fig. 1. The length and width of the GaN waveguide structure is 900 and 100 μm, respectively. The injection region begins from one end of the waveguide and extends 200 μm in length along the waveguide. The light-extraction region is located in the center of the waveguide and its surface area expands to an area of 125 μm by 125 μm. The remaining surface area of the waveguide is considered the waveguide region. A 50% diluted HCl solution is applied on the surface for 3 min to remove surface oxides prior to p-type metal contact deposition. An opaque 30 nm Ni and 200 nm Au p-type contact is deposited by electron-beam evaporation. Then, a 920 nm thick five-layer GRIN TiO_2–SiO_2 coating is deposited by co-sputtering. Co-sputtering of TiO_2–SiO_2 is performed using a SiO_2 and TiO_2 target; each target is sputtered using a separate RF generator. By controlling the deposition ratio of TiO_2 to SiO_2, the composition and refractive index of the co-deposited material can be tuned. The mesas are defined by inductively coupled plasma (ICP) etching (fluorine-based chemistry) of the GRIN coating followed by ICP etching (chlorine-based chemistry) of the p-type GaN. Subsequent ICP etching of the dielectric coating masked with photoresist results in micro-pillar arrays of GRIN TiO_2–SiO_2 in the light-extraction region of the GaN waveguide LED test structure. Micro-pillars of diameters 10, 8, 6, 4, and 2 μm with 4 μm spacing arranged in square or triangular lattices are defined using contact photolithography. A Ti/Al/Ni/Au contact layer is then deposited on the n-type GaN layer.

Electroluminescence (EL) is measured for the GRIN TiO_2–SiO_2 micro-pillar arrays on the GaN waveguide LED test structure. The devices are biased at a constant current of 5 mA and their light emission is collected by an optical multimode fiber (core diameter approximately 100 μm) located 50 μm above the sample surface, and coupled to an optical spectrometer. The EL is measured at various positions along the waveguide. The initial optical fiber position is centered 300 μm from the waveguide edge, as illustrated at the top of Fig. 2. The EL intensity is normalized at a fiber position (center of fiber) of 350 μm. At this position, the fiber is over the waveguiding region and the edge of the fiber is aligned to the boundary between the waveguiding region and light-extraction region.

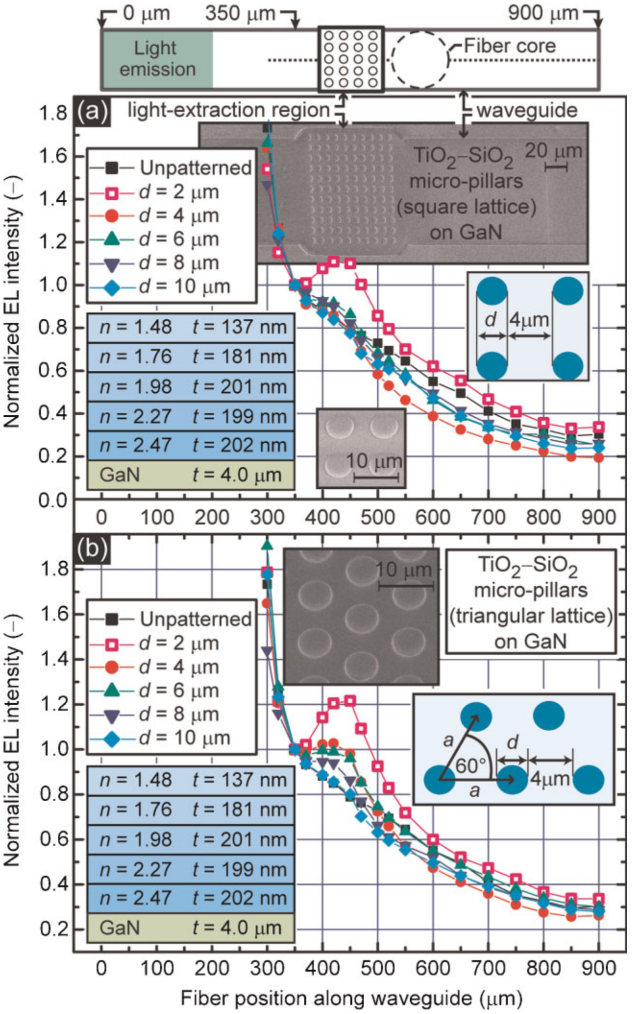

Figure 2 (online color at: www.pss-a.com) Position-dependent EL of GaN waveguide LED structure with GRIN TiO_2–SiO_2 micro-pillars for a (a) square lattice and (b) triangular lattice in the light-extraction region. Insets include SEM images of a fabricated waveguide, square lattice micro-pillars, and triangular lattice micro-pillars. EL intensities are normalized at a fiber position of 350 μm.

3 Results and discussion

Position-dependent EL measurements for the GRIN TiO_2–SiO_2 micro-pillar arrays on GaN waveguides with various pillar diameters are shown in Fig. 2(a) and (b) for a square and triangular lattice, respectively. Scanning electron micrograph (SEM) images of the fabricated waveguide as well as micro-pillars with a square and triangular lattice are shown in Fig. 2. These measurements are taken normal to the GaN surface. The fiber collection angle is nominally 25° and may be slightly larger due to non-ideal fiber cleaving. The measured intensity decreases along the waveguide due to scattering and absorption from the top or bottom of the waveguide. As the fiber is positioned over the light-extraction region, the measured intensity from the unpatterned GRIN TiO_2–SiO_2 GaN waveguide continues to decrease. However, waveguides with GRIN TiO_2–SiO_2 micro-pillar arrays show intensity enhancements compared to the unpatterned GRIN TiO_2–SiO_2 GaN waveguide within the light-extraction region. The EL intensity over the light-extraction region increases with decreasing pillar diameter such that the 2 μm diameter pillar array out-couples the optical modes most effectively. For a GaN waveguide with 2 μm diameter GRIN TiO_2–SiO_2 pillars, the peak LEE enhancement when measured at a fiber position of 450 μm is 40 and 54% for a square and triangular lattice, respectively, compared to a GaN waveguide with unpatterned GRIN TiO_2–SiO_2. The peak LEE is higher for the waveguides with triangular lattice of micro-pillars compared to waveguides with square lattice of micro-pillars possibly due to the increased rotational symmetry and micro-pillar density in the lattice, which will extract more guided modes through the micro-pillar sidewall.

The GRIN micro-pillar arrays on GaN waveguides enhance the LEE compared to an unpatterned GaN waveguide due to the extraction of light through the sidewalls of the micro-pillars. The micro-pillar arrays can also be composed solely of TiO_2, which is indexed matched to GaN. As shown in Fig. 3, guided modes can be extracted through the sidewalls of the TiO_2 micro-pillars or the GRIN TiO_2–SiO_2 micro-pillars. While all optical modes in the waveguide region are guided modes, once a mode enters into the light-extraction region, it can be considered a guided mode (light within the critical angle that would otherwise escape through the GaN waveguide sidewalls) or trapped guided mode (light not within the critical angle). However, trapped guided modes cannot escape through the sidewalls of the TiO_2 micro-pillars. In a GRIN TiO_2–SiO_2 micro-pillar, a larger escape cone exists between a TiO_2–$(TiO_2)_x(SiO_2)_{1-x}$ interface compared to a TiO_2–air interface. In the GRIN TiO_2–SiO_2 micro-pillar, this large escape cone allows trapped guided modes that enter into the TiO_2 layer to refract into the $(TiO_2)_x(SiO_2)_{1-x}$ layer above it. Then, the optical modes can escape out the sidewall of the GRIN micro-pillar, as shown in Fig. 3, or refract into the layer above. To maximize LEE, the refractive index profile of the GRIN TiO_2–SiO_2 is designed such that each layer has complementary or overlapping escape cones between its top layer interface and sidewall. The micro-pillars can extract the trapped guided modes while reducing the mean optical path length of the guided optical modes resulting in LEE enhancement and stronger pillar-side emission. We expect based on the presented analysis and on previously demonstrated simulations [11] that GRIN TiO_2–SiO_2 micro-pillars will extract more optical modes than TiO_2 micro-pillars of similar micro-pillar dimensions and lattice.

Three-dimensional ray-tracing simulations are performed to predict the effects of micro-pillar arrays on GaInN LEDs. The simulated semiconductor consists of 3.5 μm n-type GaN and 500 nm p-type GaN. The light source is a 2D sheet distributed across the width of the LED chip and located at the pn-junction plane. The simulated 1 × 1 mm^2 GaInN LED structure consists of five-layer GRIN TiO_2–SiO_2 micro-pillar arrays with 10, 8, 6, 4, and 2 μm pillar diameters and 4 μm spacing on n-type GaN.

The simulated far-field emission patterns of GRIN TiO_2–SiO_2 micro-pillar arrays as a function of pillar diameter on GaInN LEDs are shown in Fig. 4. The far-field patterns have a bi-lobed shape originating from the extraction of light through the sidewalls of the pillars. Previously demonstrated simulations have shown that LEDs with GRIN TiO_2–SiO_2 micro-pillars have higher LEE compared to LEDs with TiO_2 micro-pillars of similar micro-pillar dimensions and lattice [11]. Inspection of Fig. 4 reveals that the LEE increases with decreasing pillar diameter for LEDs with GRIN TiO_2–SiO_2 micro-pillars. The LEDs with 4 and 2 μm diameter GRIN TiO_2–SiO_2 micro-pillars have the highest LEE. LEDs with 2 μm diameter GRIN TiO_2–SiO_2 micro-pillars have higher LEE than LEDs with 2 μm diameter (1 μm thick) TiO_2 micro-pillars.

Large diameter GRIN micro-pillars could allow trapped modes to refract inside the GRIN layers without ever

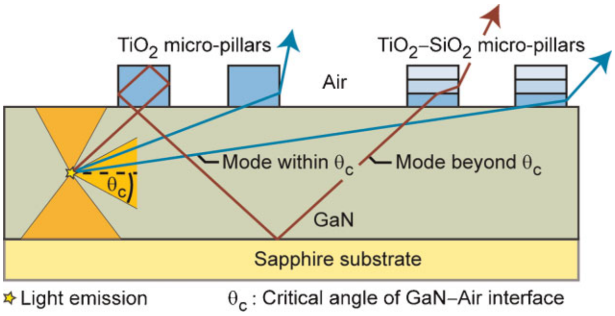

Figure 3 (online color at: www.pss-a.com) Light propagation of optical modes in a GaN slab for TiO_2 and GRIN TiO_2–SiO_2 micro-pillars on the GaN surface.

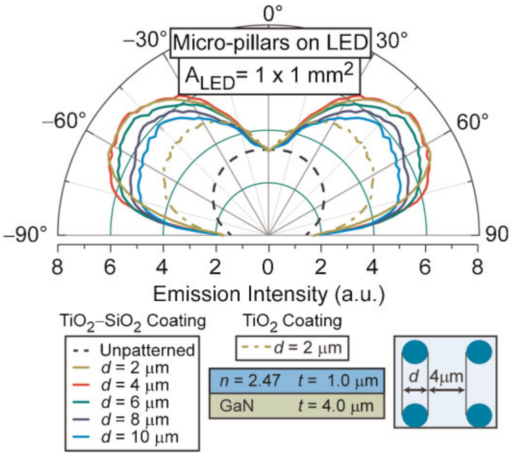

Figure 4 (online color at: www.pss-a.com) Far-field pattern simulated by ray tracing of a 1 × 1 mm^2 GaInN LED chip with five-layer GRIN TiO_2–SiO_2 micro-pillar arrays of 10, 8, 6, 4, and 2 μm diameter with 4 μm spacing on GaN and of an unpatterned GRIN TiO_2–SiO_2 LED.

reaching the pillar sidewall. Small diameter GRIN micro-pillars are predicted to have high LEE values due to the increased probability of extracting otherwise trapped modes through the pillar sidewall. However, as the pillar diameter approaches zero, the micro-pillars will have a diminishing effect. As shown in Fig. 2, experimentally we observe that waveguides with the 4 and 2 μm diameter micro-pillars have the largest LEE enhancements compared to waveguides with larger micro-pillar diameters. Waveguides with the 2 μm diameter micro-pillars, however, have larger measured enhancements than predicted by the simulations shown in Fig. 4. A possible reason for the larger enhancements could be due to the increase in tilt angle of the 2 μm pillar diameter sidewall resulting in higher light extraction efficiency values compared to micro-pillars with vertical sidewalls.

4 Summary The LEE of micro-pillar arrays on the surface of a GaN waveguide LED test structure is investigated. A GaN waveguide structure with micro-pillar arrays is designed and fabricated to measure the extraction of optical modes that would be waveguided in the absence of the pillars. EL measurements demonstrate an LEE enhancement of 54% for GaN waveguides cladded with a triangular lattice of GRIN TiO_2–SiO_2 micro-pillars of 2 μm diameters compared to GaN waveguides cladded with an unpatterned GRIN TiO_2–SiO_2 layer. Analytical theory and ray-tracing simulations of the patterned waveguides predict extraction of optical modes through pillar sidewalls. The demonstrated LEE enhancement for micro-pillar arrays of GRIN TiO_2–SiO_2 on GaN waveguides is consistent with analytical theory and ray-tracing simulations.

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